Methods and techniques for increasing the accuracy of continuous non-invasive blood pressure measurement under dynamic loads

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Abstract. In this paper, various methods for measuring blood pressure (BP) are considered and discussed in detail. Among those, we focus on the indirect BP measurement using the volume clamp method (VC). We considered a hardware solution using the SAKR-2 (Ltd Intox) device for non-invasive BP measurement. Based on our experimental results, this solution is well suited to BP dynamics measure for the patients both at rest and during movement. Specifically, by analyzing the characteristics of multiple measured results in different scenarios, we have proposed several post-processing techniques to remove the systematic errors during measurements (e.g., due to the measurement condition) and enhance accuracy. Compared to the conventional direct BP measurement methods in the radial artery (RA) using commercial device (S5 monitor), both systolic blood pressure (SBP), diastolic blood pressure (DBP) indicators have strong relationship. The measured BP shifts with respect to hydrostatic changes in blood pressure are fairly match to the theoretical predetermined value during repetitive measurements.

Keywords: Medical applications; Blood pressure sensors; Continuous non-invasive blood pressure measurement; Embedded measurement systems.

1 Introduction

Measurement of blood pressure (BP) essentially is one of the most commonly important measurements used in outpatient, inpatient facilities, as well as in everyday life because it provides important indicators of the physiological processes of the patient's cardiovascular system.

For more than a hundred years, the scientific community has made great efforts to develop algorithms and techniques for the implementation of blood pressure measurement devices using indirect measurement approaches. BP direct measurement undoubtedly is one of the most widely adopted BP measurement methods in cardiology practice during surgery, in intensive care units and also for research purposes [1].

This method typically is carried out for a relatively limited range of indicators and does not require either a complicated interpretation of physical processes or a highly accurate measuring system [2]. Nonetheless, this method remains fundamentally an invasive approach, where the complexity of the measurement procedure significantly simplifies the instrument design. The main advantages of non-invasive (indirect) methods are the exclusion of trauma, protecting the integrity of the patient's skin and eliminating the risk of infection [3-4].

From other point of view, in any measuring system, it is a necessity to take into account the dynamic properties of the target signal. Specifically, in BP measurement, BP reflects hemodynamics and continuously on each heartbeat. Instantaneous BP values are represented by a pressure pulse. The characteristic parameters of the pulse are distinguished by anacrotic rise, dicrotic wave, and incisura [5]. Capturing the pattern of the BP signal is the most difficult task in non-invasive measurements. Most instruments allow to evaluate BP using extremals of systolic blood pressure (SBP) pulse, diastolic blood pressure (DBP) or based on empirical relationships. They also are able to quantify the BP pulse (PBP) and average pressure as an integral indicator calculated from a series of heartbeats [7].

Non-invasive BP measurement methods can be conditionally divided into the following groups (see Fig. 1):

- methods for measuring BP parameters by compressing the vascular system in a single compression-decompression cycle of air in the cuff;
- continuous BP measurement methods.

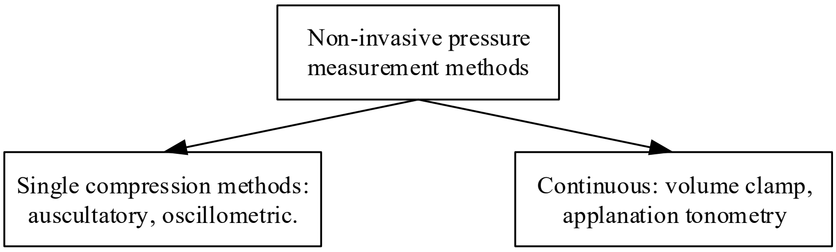

Fig. 1. Classification of BP measurement methods

In medical practice, the Korotkov method [8] has been long recognized as the “golden standard” for BP measuring. This method calculates the estimated pressure value indirectly extracted from a series of brachial artery pulses. However, this method permits evaluating only one SBP and DBP value per single measurement, and the resulting values vary with respect to different heartbeat periods. The error of the method hence is statistically determined by the magnitude of the variations in SBP, DBP and the rate of pressure decrease in the cuff. This leads to inevitable ambiguity in determining the SBP as the presence of "auscultatory failure" (short-term disappearance of Korotkov tones) and does not allow determining the blood pressure in patients with severe rhythm disturbance. This is due to the fact that BP pattern is significantly different at every heartbeat [9].

Korotkov’s method is suitable for characterizing and extracting diurnal BP dynamics from periodic measurements, meanwhile, in various types of medical diagnosis and research, the instantaneous pressure caused by shorter heartbeat may reflect important information. Continuous measurements permit recording in detail the reaction of the cardiovascular system to a given external load (orthostatic test, stress test, etc.) [10-12]. Despite the fact that the measured value is associated with a short period, it carries significant information about the dynamics of the system, and the transient process can be further used to characterize the system during a short measurement.

Among non-invasive continuous BP measurement methods, the volume clamp (VC) (known as the Peňáz method) is one of the most popular methods. As the fundamental principle, BP measurement is carried out using a pneumatic cuff on a finger [13]. The reliability of measured BP by the Peňáz method has been solidly proven both for patients at rest [14–16] and for patients in BP changing conditions (such as an orthostatic test) [17, 18]. Nonetheless, these works focused only on comparing the average blood pressure obtained by various methods while the accuracy in recording pressure dynamics and variations for every single heartbeat were not considered in detail.

This paper systematically studies the accuracy aspect of the BP measurement using the volume clamp approach. We then proposed techniques for enhancing the reliability of the measured BP for the patient both at rest and during movement condition.

The remaining of the paper is organized as follows. Section 2 describes the research methodology and the experimental setup. Section 3 presents and compares the main experimental results. Further development and enhancement techniques are discussed in Section 4 before the conclusions are drawn in Section 5.

2 Methodology and Experimental Setup

The VC method in this work has been implemented using an embedded hardware platform. In particular, we adopted the Spiroarteriocardiorhythmograph (SAKR-2) system from Ltd. “Intox” discribed in the study [19, 20], whose structure is shown in Fig. 2.

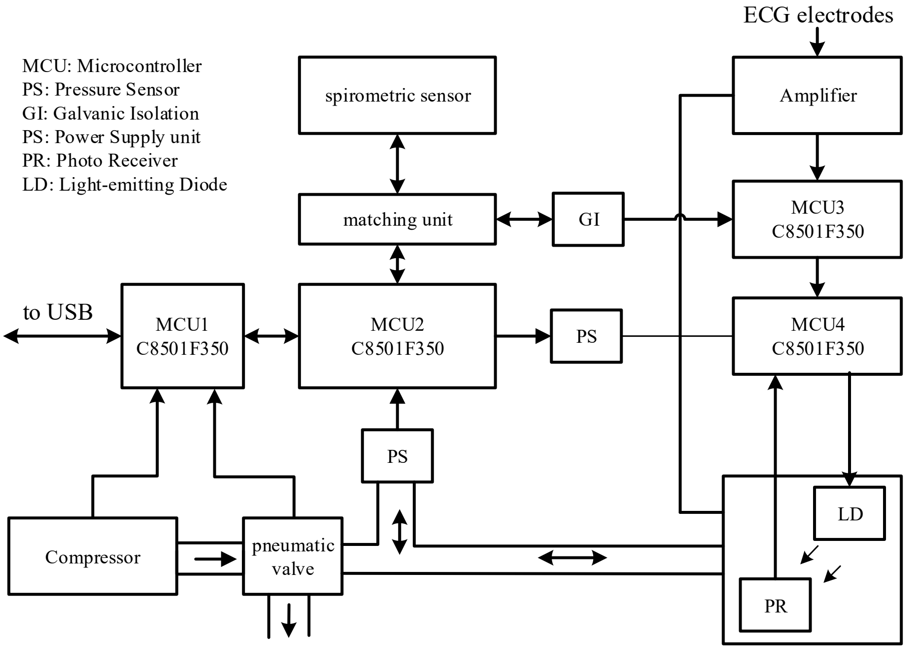

Fig. 2. Block diagram of the electronic-pneumatic device «SAKR»

The SAKR-2 device based on the VC method is calibrated and configured before every BP measurement. During the setup, a tacho-oscillogram is used for estimating SBP, DBP and average pressure values. The obtained parameters then are used to set the initial settings for continuous BP measurement using the VC method. The measurement device does not yet support correction for peripheral pressure components associated with the shoulder. The latter basically is a hydrostatic pressure component caused by the relative height of the finger position with respect to the heart. The measurement devices either have no post-processing for the values measured in the shoulder. This leads to interesting questions: how accurately the device registers small-scale physiological pressure fluctuations, and how accurately the device reproduces the pressure curve during significant and abrupt measurement condition shift from the original setting. In fact, the accuracy of recording changes in pressure is especially noticeable when monitoring pressure during stress tests.

Evaluation of the accuracy in measuring the BP dynamics using the VC method was carried out in two series of experiments:

1. comparison of pressures obtained by the method of RA and direct method;
2. checking the coincidence of theoretical and measured pressure in the finger with “hydrostatic” changes in blood pressure by a predetermined value.

The measurements were carried out at the Scientific Institution of Experimental Medicine. The study involved seven patients aged from 39 to 76. In a motionless patient, the BP was simultaneously recorded by the direct method with RA on the left hand and the VC method on the right-hand finger.

Direct measurement of blood pressure was performed using a bedside S5 monitor from Datex-Ohmeda [21]. Accordingly, an invasive sensor recorded blood pressure in the radial artery. The measurement results were displayed every 5 seconds.

From the quantified SBP and DBP values, the constant component, calculated by averaging recorded BP signals, was removed in order to extract the BP variable components. The constant component then was analyzed separately. For the variable component, we adopted a statistical method to quantify the accuracy of recorded BP dynamics using the VC method. Specifically, the standard deviations and correlation coefficients between the BP values measured by the invasive method and the SAKR-2 device were statistically evaluated and compared.

In the second series of tests, the dynamics of blood pressure measured on the finger for every single heartbeat was compared with the pressure measured on the wrist by the oscillometric method with significant changes in BP in the limb. The change in pressure was set by the vertical movement of the limb relative to the heart level. With a vertical movement of an unstressed arm, finger pressure *P(h)* (in mmHg) is determined by the following formula:

$$(h) = P_0 + \frac{\rho_K}{\rho_{Hg}}(h_0 - h) + \Delta P \qquad (1),$$

where P_0 is the systolic or diastolic pressure in the finger at a height of h_0; ρ_K is the blood density, ρ_{Hg} is the density of mercury, h is the current height of the finger, ΔP is the pressure variation due to respiration, the influence of the baroreflex and other physiological factors.

A change in the height of the hand relative to the level of the heart leads to a noticeable pressure drop. Accordingly, pressure variations can introduce not only random but also systematic errors, for example, associated with the influence of a baroreflex during hydrostatic changes in peripheral pressure. An Omron R2 tonometer, which measures pressure on the wrist, was used as a monitoring device. The tonometer indicator values were used to exclude the systematic error caused by the physiological characteristics of the subject.

The methodology of these studies was as follows. The subject's hand in an extended relaxed position was located on a convenient stand, this stand can be rotated to two fixed positions relative to the subject's shoulder. The fixed positions were chosen so that the height of the cuff changed exactly by 520 mm, which corresponds to a change in pressure of 40 mmHg. In each of the fixed positions, a pressure measurement was performed with a tonometer after 10 s displacement. Averaging was carried out according to the results of five measurements in each position.

Measurements by the SAKR-2 device were performed in a similar manner. i.e., the subject's arm in an extended relaxed position was located on a convenient stand, which can be rotated to two fixed positions. The device setup was carried out in the upper arm position, then the device performed continuous BP measurements. For every 15 seconds, the stand with the hand rotates to the opposite fixed position. The positions were carefully chosen so that the height of the finger with the cuff changed exactly by 520 mm, which corresponds to a 40 mmHg change in BP.

The average BP values measured by the SAKR-2 device in each of the stationary positions were compared with the average BP values measured by the Omron R2 tonometer. Changes in systolic (SBP), diastolic blood pressure (DBP) and pulse blood pressure (PBP) relative to the highest pressure were analyzed. The detail is presented and discussed in the subsequent section.

3 Experimental Results

3.1 Comparison of non-invasive BP measurement in the finger and invasive BP measurement in the radial artery at rest

The BP dynamics are most clearly manifested when observing the BP variable components retrieved from the direct method and recorded by the SAKR device for every single heartbeat. For this purpose, the average level during the synchronous measurement was previously removed from the recorded data. In fig. Figs. 3-4 show examples of SBP dynamics in direct synchronous measurements using the S5 monitor and SBP measured by SAKR-2 using the VC method.

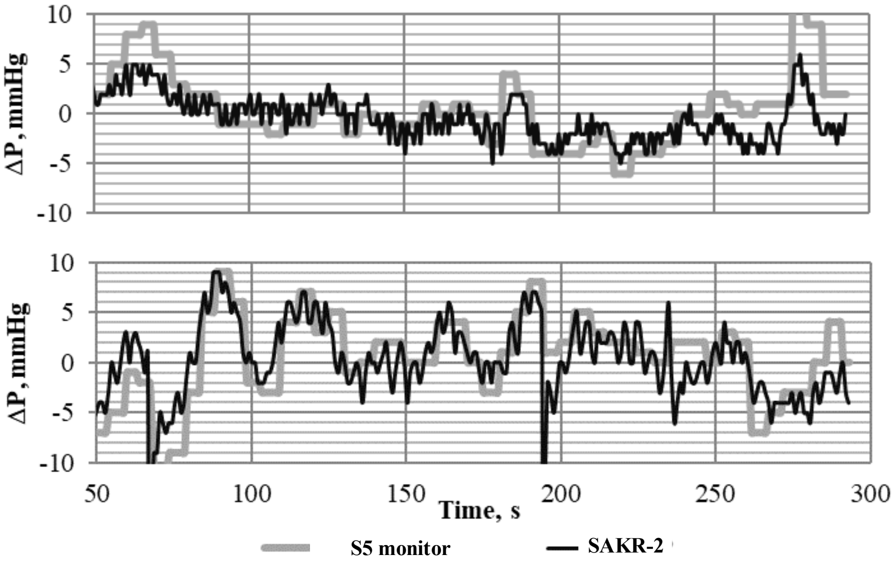

Fig. 3. Comparison of resting SBP variations during synchronous measurement by a S5 monitor in the radial artery and by the SAKR-2 in the finger.

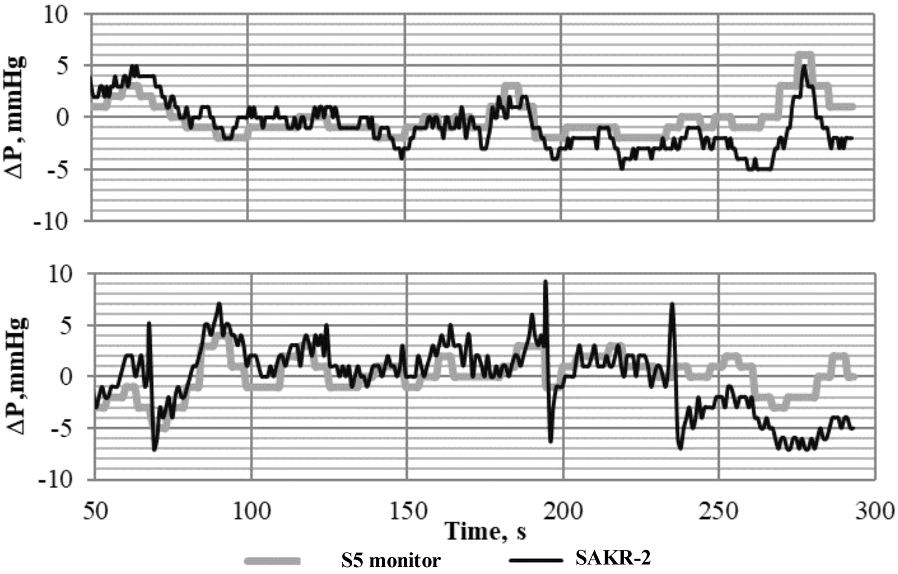

Fig. 4. Comparison of the DBP variations at rest during synchronous measurement by the S5 monitor monitor in the radial artery and by the SAKR-2 in the finger.

From the graphs presented in Figs. 3-4, the overall recorded signals patterns using S5 monitor and SAKR-2 are very much in line. However, there is a large discrepancy in the absolute value due to the averaging effect in the invasive devices. On the last graph, extrasystole moments are visible that did not appear on the monitor due to averaging of invasive results. The standard deviation for SBP and DBP is summarized in Table 1. The correlation coefficient calculated for zero time lag between signals.

Table 1. The standard deviation and correlation coefficients calculated from synchronous BP measurements by the SAKR-2 device and direct BP measurements in the radial artery after removal of the stationary components.

#	Std Dev* SBP, mmHg	Std Dev* DBP, mmHg	r** SBP (p-value)	r** DBP (p-value)
1	3.3	2.9	0.5 ($p < 0.05$)	0.3 ($p < 0.05$)
2	3.0	2.0	0.5 ($p < 0.05$)	0.6 ($p < 0.05$)
3	2.0	1.6	0.9 ($p < 0.05$)	0.7 ($p < 0.05$)
4	1.6	1.0	0.8 ($p < 0.05$)	0.9 ($p < 0.05$)
5	3.5	3.1	0.7 ($p < 0.05$)	0.4 ($p < 0.05$)

Std Dev: standard deviation, r: correlation coefficient, p : probability value.

From Figs. 3–4, there is a notable gradual pressure drift when measured by the SAKR device caused by the change in the blood supply to the finger. After performing a linear approximation on the data, we found that, on average, systolic pressure (diastolic pressure) decreases at a rate of 0.02 ± 0.001 mmHg/s (0.025 ± 0.007 mmHg/s). The described signal attenuation in a five-minute recording possibly causes a pressure decrease of 6 mmHg. The drift in the first minutes of measurement by the VC method is associated with the displacement of blood from the capillary vessels, which affects the constant level of the photo signal in the finger. This drift takes 3-5 minutes. After this time, it is necessary to repeat the adjastment of the control system.

3.2 Quantifying the accuracy of the BP measurement under a significant measurement condition change

To determine the level of BP changes using the hydrostatic method, we used an Omron R2 carpal tonometer as the reference for the BP shift. Table 2 shows the differens between results of BP measurement in different arm level. results are presented for oscillometric method (Omron R2) and VC method (SAKR-2).

Table 2. Measured BP shift with lowering of the arm by 520 mm (predicted change is 40 mmHg).

№	Oscillometric method (Omron R2)			Volume clamp method (SAKR-2)		
	ΔSBP ± Std Dev, mmHg	ΔDBP ± Std Dev, mmHg	ΔPBP ± Std Dev, mmHg	ΔSBP ± Std Dev, mmHg	ΔDBP ± Std Dev, mmHg	ΔPBP ± Std Dev, mmHg
1	51 ± 10	44 ± 4	7 ± 9	49 ±3	37 ± 1	12 ± 2
2	46 ± 10	43 ± 3	3 ± 9	40 ± 5	38 ± 2	2 ± 3
3	41 ± 6	37 ± 4	4 ± 8	36 ± 6	31 ± 3	5 ± 5
Average	48 ± 9	41 ± 5	8 ± 8	42 ± 6	36 ± 3	6 ± 6

Δ – average pressure shift at different heights of the measurement point relative to the heart.

The reliability of BP measurement by the volume clamp method is strongly affected by the outflow of blood from the finger. In many cases, finger BP obtained both by the oscillometric method and by the VC method significantly exceeds the BP indicators in the shoulder. In such cases, it is observed a significant redness of the finger portion that is far from the occlusion site. This is due to the fact that the outflow of venous blood is completely blocked, thus, the average pressure of the finger area increases correspondingly. The described case is also in line with the deterioration in the reproduction of the BP pulse when measured by the VC method. After adjusting the device to lower the pressure in the limb, raising it relative to the level of the heart, the diastolic pressure practically does not change, while the systolic pressure significantly decreases.

4 Discussion on further improvements

The blood pressure profile measured by the SAKR-2 showed many similarities to the BP profile obtained by the direct measurement method in the radial artery (stdandatr diviation of resalts less then 3.5 mmHg). In all cases, signal dependences are observed (p-value < 0.05), the correlation coefficients of SBP are greater than 0.5.
The linear trend, observed during the first minutes of measurement by the RA method, is associated with the displacement of blood from capillary vessels, which affects the constant level of the photo-signal in the finger. This blood displacement occurs within 3-5 minutes. After this period has passed, it is necessary to recalibrate the control system. Alternatively, a preliminary procedure for stabilizing the photo signal (displacing blood from under the finger cuff) with excessive pressure can be conducted. During this procedure, the transient response of regulation would be determined by the dynamic characteristics of the photo signal associated with a particular patient.

In absolute measurements of blood pressure by the direct method in the radial artery and by SAKR-2 in the finger, very often, significant differences between two approaches, especially regarding the diastolic blood pressure, were observed. The discrepancy may be due to a combination of the following factors:

- measurements were taken in various places of the arterial bed. As the pulse wave advances, its shape and amplitude change due to changes in the resistance and stiffness of the vessels.
- the heights of the forearm and finger relative to the heart were not taken into account.

Obtaining the usual estimations of blood pressure, corresponding to measurements in the shoulder at the level of the heart, requires constructive and algorithmic techniques for improving the measuring system.

It is required to develop a system for adjusting the values of peripheral BP at the shoulder for each measurement. Due to significant changes in the signal at different heartbeats, signals describing hemodynamics in the shoulder should be simultaneously recorded while measuring the BP pressure in the finger. The correction value should be based not only on final integral indicators, such as SBP and DBP but on the corresponding continuous signals recorded at different parts of the system (BP signal from the shoulder cuff, finger cuff, microphone, ECG, photo signal, etc.).

One possible solution for BP correction is to use an additional finger sensor. This reference value helps automatically adjusting the pressure change during the movement of the patient’s arm. Nonetheless, with changing the patent's body position during measurement (e.g, during an orthostatic test), this technique may not guarantee good level of accuracy.

Analyzing the total existing features of the BP measurement system, it is suggested that potential techniques for correcting measurement results should be based on intelligent data processing algorithms, i.e., machine learning approaches. The structure of such a correction system is shown in Fig. 5. In the proposed system, all modules are implementable on embedded hardware. This will be our main focus in future work, detailed discussion on that structure is beyond the content of this paper.

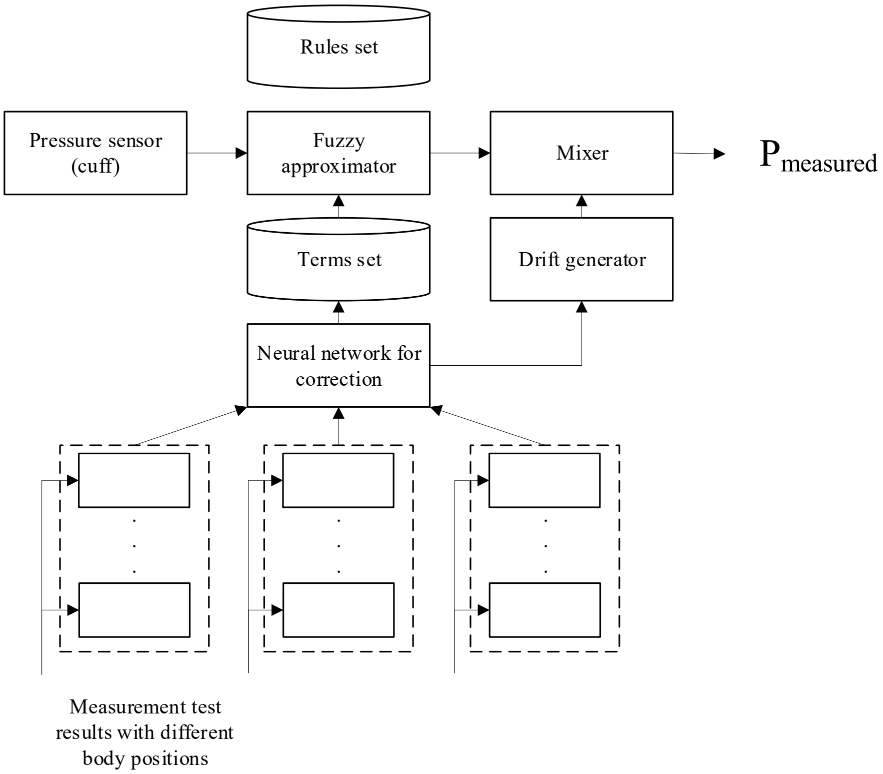

Fig. 5. The structure of the correction system for BP measurement

Data from the pressure sensor needs to be intelligently corrected in depends on a large number of parameters. In addition to the body positions, following parameters may affect the result: the pulse wave propagation velocity, the error in the regulation of the photo signal, the heart rate, etc. These parameters are sent to the neural network. The results of the neural network through a set of terms are provided to a fuzzy aproximator, which corrects the original signal.

5 Conclusions

The method that measures BP for a single heartbeat in the finger is well-suited for use under physical activity, in which the change in BP relative to the resting state is used to evaluate the final results. Despite the fact that this method is non-invasive, it still is capable to record continuously the relative BP dynamics with a fairly high level of accuracy. With potential further improvements proposed above, this BP measurement method could potentially replace and eventually overcome distinct disadvantages of the conventional invasive BP measurement method in majority cases of medical practice.

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